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REVIEW OF CAPACITOR SWITCHING EFFECTS ON POWER QUALITY

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ABSTRACT

Capacitor switching surges are generally modest in level compared to other transients seen by electrical customers due to load switching, lightning or system faults. However, capacitor switching may be responsible for the following particular stresses. Firstly, daily switching of capacitors can lead to the failure of deteriorating equipment since other sources of surges may be less frequent. Secondly, the duration of capacitor switching transients could be long enough (up to several milliseconds) to thermally overload surge protectors, installed to limit microsecond duration surges. Thirdly, the fast voltage dip associated with energizing an uncharged capacitor bank may prevent thyristor firing, thus causing a variable speed drive to trip. The second and third areas do not appear to be well addressed by current standards and are covered by only a small number of technical references.

INTRODUCTION

Power quality is the degree to which the electrical service to a customer is free of steady-state harmonics or transient disturbances. While harmonics or disturbances cannot be eliminated, they can be controlled and quantified. Thus customer-owned equipment can be specified, designed or modified to be compatible with limiting values.

Capacitor banks are used by many customers and most utilities to improve the local power factor. By compensating for the lagging current drawn by transformers, motors or fluorescent lamps; losses are reduced and drooping voltages supported. During the night when loads are reduced, capacitor banks may have to be switched out of service to prevent excessive voltage rise.

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Switching a capacitor bank into service always produces a momentary disturbance which travels through lines and transformers to reach every customer. It can be readily detected by power line monitors. Switching a capacitor bank out of service normally produces a much smaller transient which probably would not be seen by monitors. Occasionally, for particular types of switchgear, restrikes can occur on bank de-energization which may produce larger disturbances than on bank energization. All of these events have been extensively quantified, both through tests and simulations of the power system.

The purpose of this report is to review power quality parameters seen by customers when capacitor banks owned by electrical utilities are switched. The focus is on industrial variable speed drives where a drive shutdown may result in lost production and expensive system start up. Only transient disturbances, and not steady-state harmonics, are covered. Five power quality parameters are discussed, covering long-term voltage deviations to steep-fronted surges. Each parameter section quantifies the level of possible disturbance, compares this level to the "background noise" of other sources normally present and discusses the possible vulnerability of customer-owned equipment to these stresses.

POWER QUALITY PARAMETERS

1. Long-Term 60 Hz Undervoltages or Overvoltages

Capacitors banks are sized so that their energization typically raises the 60 Hz voltage by several per cent. This may be compensated by a tap changer having 1.5% steps after a few seconds. The opposite occurs on de-energization. Larger changes in voltage at the customer may be caused by load variations through the day.

Sensitive loads may include computers and variable speed industrial drives. For the latter, the sensitivity is quantified in IEEE Std 597, "Practices and Requirements for General Purpose Thyristor DC Drives"/1/. This standard indicates that uninterrupted operation shall result for voltages from 90 to 110% of the rated value. Thus capacitor switching has a minimal effect on this power quality parameter.

2. Short-Term 60 Hz Sags or Swells

De-energizing a capacitor bank reduces the voltage by several per cent within a fraction of a cycle. In comparison, faults on the power system can result in customer voltages on one or more phases between 0 to 100% of the nominal value for 2 to 120 cycles, depending on the closeness of the fault and the breaker characteristics. Sags to 50% voltage or less on at least one phase might occur between 1 and 10 times a year for a given customer. Undervoltage sensing contactors could drop out for voltage below 60% for more than 2 cycles/2/. For variable speed drives, IEEE Std 597 appears to allow shutdown for sags of only one cycle below 90 per cent rated voltage/1/.

Swells can occur when a capacitive load is fed by a relatively high source inductance. Voltage rises to 120% of the nominal value for 2 to 5 cycles may result when faults on high voltage (>100 kV) capacitor banks, cables or long lines are temporarily backfed through transformers with parallel secondaries. This could thermally overstress metal oxide varistors applied with insufficient temporary overvoltage capability.

3. Submillisecond Range Voltage Notches

Capacitor switching normally introduces voltage dips to zero (or beyond zero on some phases) for durations ranging from about 0.1 to 1 ms. For variable speed drives this may lead to commutation failure followed by tripping of the drive. IEEE Std 587 states that voltage dips exceeding 0.5 per unit (per unit base is nominal peak line-to-ground voltage) lasting longer than 100 μs should be jointly reviewed by the purchaser and manufacturer/3/. Thus, customers who wish a complex industrial process to remain on-line through utility capacitor switching should specify this capability explicitly to the manufacturer.

4. Microsecond Range Surges

Microsecond surges may result from the arcing associated with switches opening on the customer's premises, lightning, or the steep-fronted component associated with capacitor energization. A study has shown that the natural surge environment in low voltage wiring probably exceeds 2 kV and is limited to 5 kV in low voltage wiring systems/4/. This corresponds to 4 and 10 per unit respectively for 600 V systems. These levels are further supported by IEEE Std 587, "Guide for Surge Voltages in Low-Voltage AC Power Circuits," suggesting that protective systems be designed to accommodate surges of 6 kV/5/.

Since 1952 Ontario Hydro Research has recorded capacitor switching transients at more than 25 stations/6/. Reports are available showing that the measured surges can be successfully modelled and are reasonably predictable for any customer/7/. In the following, the effect of switching an Ontario Hydro 28 kV bus capacitor bank was calculated for an industrial customer with 600 V equipment. It was assumed that an intermediate voltage level, eg 4160 V, was present and that all transformers were connected delta/wye. The results are as follows:

a) closing may result in a fast dip from peak voltage to zero (or beyond zero) followed by a damped transient oscillating about one per unit with a frequency of about 400 Hz. The additional zero crossings may be introduced into one or more phases. The peak overswing of the 400 Hz component should be limited to 1.5 per unit or 730 V on a 600 V system.

b) for load at the end of a radial feeder, steep-fronted surges associated with multiple reflections may extend the initial fast dip to nearly -1.0 per unit. The reflections can also add to the 400 Hz overswing to give a total surge with peak approaching 2.0 per unit or 980 V.

c) if local capacitor banks or long cables are present and the customer load is light, there is a distant possibility of local resonance with the 400 Hz closing transient. This could raise the total surge voltage to about 2.7 per unit or 1320 V.

d) a restrike on de-energization of the capacitor breaker under extreme cases could raise these levels to about 5 per unit or 2400 V. This is considered highly unlikely for air blast, SF_6 or vacuum breakers which are considered restrike-free when faced by their normal duty and properly maintained.

e) transformers of high ratio, for example 28 800/600 V, could amplify surges seen on the LV base since the capacitive division ratio may exceed the turns ratio. This applies only to the steep-fronted portion of the surge which from b) above is limited to 2.0 per unit. The result should be surges well under 5 per unit, with special tests needed to more accurately quantify this mechanism for a particular site.

The electrical strength of customer-owned equipment should have a minimum dielectric withstand proven through a 60 s power frequency test of (1 kV + 2 x nominal phase-to-phase voltage) applied between each terminal and ground/8/. For 600 V equipment this corresponds to 6.4 per unit. Certain insulation, such as found in motors, is capable of a higher withstand for surges than power frequency. North American manufacturers have agreed to a surge rating of 1.25 times the above power frequency test corresponding to 8.0 per unit. For surges with a front of 1 μs, this value is derated to about 2.5 per unit/9/. More specifically for variable speed drives, IEEE Std 597 states that 321 - 640 V rated equipment shall be tested by applying 6.3 kV surges from a specified test circuit/10/. Normally, manufacturers can efficiently control the effect of microsecond range surges using surge capacitors and metal oxide varistors.

5. Millisecond Range Surges

As mentioned above, capacitor energization at transformer stations also typically produces a 400 Hz transient decaying in a few milliseconds with maximum level of 1.7 per unit. For a small number of sites, resonances in cables or low voltage power factor capacitors could raise this to 2.7 per unit or about 1320 V for a 600 V system. Varistors for ungrounded 480 V systems may typically be rated 510 V/11/. Such varistors could be thermally overloaded by a train of surges of level 1000 V with durations of about 1 ms. Presumably, ratings are scaled proportionately higher on 600 V systems. The solution recommended in the reference is to use varistors with sufficient energy capability and to apply additional arresters at an intermediate voltage bus.

The above energy duty is on the order of 100 joules. Inspection of IEEE Std 597 shows that the specified impulse test for equipment rated 321 to 640 V results in much less than 33.5 J being dissipated in the device due to the limited surge duration/11/. Thus, this standard is not sufficient in itself to protect equipment against longer duration surges.

Similar constraints can apply to distribution voltage arresters which may be installed to intercept millisecond range surges before reaching the customer/11/. Calculations show that 3 kV distribution class arresters installed on a 4.16 kV system have an energy rating capable of withstanding 2.0 per unit surges for a duration of several milliseconds. This severity of surge is not reached on normal switching but could occur for the event of the capacitor circuit breaker restriking. This contingency is considered highly unlikely for air blast, SF_6 or vacuum switchgear properly rated and maintained. Air magnetic circuit breakers have a low probably of producing millisecond range surges exceeding 2.0 per unit in level. This calculation is also overly conservative in not assuming any sharing of energy between the large number of arresters usually found on a 4.16 kV system.

SUMMARY

Capacitor banks are sized so that long-term voltage sags or surges are well within the tolerances specified for sensitive equipment such as variable speed drives. These drives may, however, be vulnerable to other power quality parameters. When ordering such equipment, customers should discuss the following topics with suppliers. The voltage levels indicated are representative of 480 to 600 V systems.

1) system faults at remote locations may cause voltage dips between 0 and 100 per cent for 2 to 120 cycles, with the probability of larger dips being much less than small dips. Thus a ride-through-capability for modest dips, of say 10 to 30 per cent rated voltage, should significantly reduce system shutdowns.

2) capacitor switching causes a submillisecond voltage notch (0.1-1.0 ms) which may prevent thyristor firing and thus interrupt variable speed drives. This might be mitigated using a sufficiently long train of firing pulses.

3) microsecond range surges associated with capacitor switching may reach 2.5 kV. While this is less onerous than other surge sources found locally at the customer, capacitor or metal oxide varistor surge protection may be required.

4) millisecond range transient overswings associated with capacitor switching may reach 270 per cent of normal peak phase voltage. This can thermally overload metal oxide varistors with insufficient voltage or energy rating.

5) temporary capacitive voltage swells due to backfeeding of high voltage faults through transformers may raise voltages to 120 per cent for some cycles. This can likewise overload varistors.

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